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A socio-economic method for estimating future air pollutant emissions—Chicago case study

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Abstract

This paper presents the development of an econometric-emission model to formulate future anthropogenic emission inventories for different societal and climate change scenarios. Our approach is to formulate the emission projections for a given scenario into growth factors that can be used to project forward the 1999 National Emission Inventory (NEI99). The process involves (1) mapping NEI99 source classification code (SCC)-based emissions into the sector or standard industrial classification (SIC)-based representation used by the econometric model, (2) developing a sectoral emission intensity (EMI) defined as the sector emissions per unit of sector economic output and the mechanism to consider EMI variations over time, (3) using the resulting EMI with econometric models and future emission activities to project future emissions, (4) and then mapping the emissions back to the original NEI99 format. As a case study, we apply the model to project emissions in the Chicago metropolitan area. The results show that the model is a fast, flexible, yet reasonable tool to produce a wide range of emission scenarios that are specific to regions, and would prove valuable for future air quality and other impact studies.
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1. Introduction

In recent years, different studies have investigated the consequences of emissions and climate changes on regional air quality (e.g., Prather et al., 2003; Hogrefe et al., 2004; Mickley et al., 2004; Leung and Gustafson, 2005). In order to achieve future detailed air pollutant emissions necessary for a regional air quality simulation, researchers (e.g., Hogrefe et al., 2004) generally grow the current emission inventory to target future years by applying scaling factors calculated from various scenarios such as the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) (IPCC, 2000). However, such scaling factors are normally based on emission projections of a set of countries, e.g., in IPCC the Organization for Economic Cooperative Development as of 1990 (OECD90). Detailed sub-region features key to the

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formulation of an effective and feasible emission control strategy, such as local economic structures (for example, the composition of economic activity), regulations, transportation systems, and technology development levels, are not reflected in the afore-mentioned scaling factors (Prather et al., 2003). The present paper attempts to improve future emission scenarios by utilizing a regional environmental–econometric input–output (I–O) model to link pollutant emissions to economic activities, popula-tion, and transportation, and project future emis-sions that are based on forecasted regional changes.

The I–O analysis was developed by Wassily Leontief in the 1930s and since then has grown into one of the most widely used methods of economic planning and decision making. I–O analysis traces demand and supply linkages in the economy, and thus provides insight to the direct and indirect effects associated with changes of the final demand of an industry (Yan, 1969). Considering pollutants as by-products of economic activities, Leontief extended the I–O method to analyze air pollution (Leontief, 1970; Leontief and Ford, 1971). Follow-ing this pioneering work, the I–O analysis has been widely applied in economy–environment studies (e.g., Miller and Blair, 1985, and the references therein; Laitner et al., 1998; Kebede et al., 2002; Nansai et al., 2003; Wainger et al., 2004; Fung and Kennedy, 2005). The advantage of applying I–O analysis is its ability to integrate the overall environmental effects, e.g., pollutant emissions, and demand–supply interactions among economic sectors.

In this study, we extend our regional econometric input–output model (REIM) to examine air pollu-tant emissions. By establishing relationships be-tween emissions and economic activity of each sector, we project future emissions based on specific regional changes in economic structures, transpor-tation, and population. We account for the non-linear feature of emissions–economy relationship by developing the time-dependent emission intensity (EMI) based on historical emissions and economic data. Our ultimate goal is to formulate the emission projections for a given scenario into growth factors that can be used to project forward the current inventory such as the 1999 National Emission Inventory (NEI99, http://www.epa.gov/ttn/chief/eiinformation.html). The projected inventory can then be processed by an emission modeling system, e.g., the sparse matrix operator kernel emissions (SMOKE, Houyoux et al., 2000) supported by the

US Environmental Protection Agency (USEPA). During the initial stage, we apply the model to project future emissions for the Chicago metropo-litan area. The system is presently being extended to simulate future emissions over the Midwestern US.

2. Methods

Emissions are determined by the EMI and levels of emission activities:

$$EM = EMI \times activity, \tag{1}$$

where EMI characterizes the emissions per unit of activity. In this study the primary emission activity is sectoral economic outputs (in constant monetary terms) from the econometric model. Since there is no economic sector in the model dedicated to private personal economic activity, we treat resi-dential heating using a population-based activity designation. In addition, for transportation activity, vehicle miles traveled (VMT) is assumed for calculation of mobile emissions. Fig. 1 illustrates the overview of the modeling system. Our general procedure is to construct the historic EMI for each pollutant and use the past behavior that includes all factors affecting past emissions, e.g., economic activity, technological change, and emission control, to develop scenarios of future EMI behavior. In particular the strategy is to (1) utilize REIM to depict past, present, and future economic activities; (2) develop EMI based on available emission inventory and economic/social activities; (3) develop a mechanism to quantify changes in EMI related to shifts of energy and material usage, technological change, population change, and possible policy and regulation changes; (4) survey historical and pro-jected changes in emission activities, e.g., energy, population, and VMT; (5) develop future emission
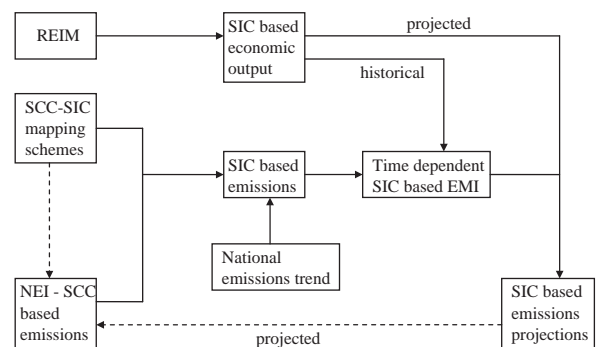

Fig. 1. Schematic overview of the econometric-emission model-ing system.

inventory based on Eq. (1); (6) and, finally, map the activity-based emissions to process-based emissions that are catalogued by the source classification code (SCC, http://www.epa.gov/ttn/chief/codes/) so that they can be used as inputs to emission process models, such as SMOKE, to generate speciated and gridded emissions at the time resolution required by air quality models (AQM).

2.1. Chicago regional econometric input–output model (CREIM)

CREIM is a computable regional general equilibrium model that combines the I–O analysis with the time series analysis to project Chicago economy over a 30-year horizon (Israilevich et al., 1997). The model identifies 53 economic sectors that can be characterized by two-digit standard industrial classification (SIC, http://www.osha.gov/pls/imis/sic_manual.html) code, and comprises 264 endogenous variables, 55 exogenous variables, 18 accounting identities, and 253 behavior equations out of which 53 are related to the linear I–O components. Many of the non-I–O equations are nonlinear and the whole systems are solved in a recursive manner. Consequently, the relationships of one sector to another take into account both the formal I–O links and a set of complex linkages through a chain of actions and reactions potentially involving the entire economy. The I–O table is constructed based on the survey data from the US Bureau of the Census. Among the final results that are derived from CREIM simulations are sectoral output and income, employment, and population growth. Since its creation, CREIM has been extensively applied in various economic and environmental studies (e.g., Hewings et al., 1998, 2001; Fritz et al., 2002; Okuyama et al., 2002).

2.2. Emission intensity (EMI)

Development of EMI is necessary for emission inventory projection. The crucial first step is to formulate EMI based on present emissions and levels of emission activities. In this study, the present emissions are represented by NEI99 that includes point, area, and on-road mobile sources (http://www.epa.gov/ttn/chief/net/1999inventory.html). We select several surrogates to represent emission activities. The first surrogate is sectoral economic output as described in Section 2.1. Data for the VMT surrogate are from the Federal Highway

Administration's Highway Statistic Publication (http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.htm). Emissions from household activities, e.g., space heating/cooling, solvent usage, and yard-waste burning, are indexed to population, which is available through the US Census Bureau (http://www.census.gov).

2.2.1. SCC–SIC mapping

NEI99 is organized and reported based on the SCC, which reflects the actual pollutant emitting process. On the other hand, CREIM uses the SIC code to group and analyze economic activities. Thus, mapping NEI99's SCC emissions to CREIM's SIC emissions is essential to generating sectoral output-based EMI. There are nearly 10,000 SCCs in NEI99 vs. 53 economic sectors used in CREIM. In NEI99, all point source SCCs and approximately 16% of nearly 1200 area source SCCs have an associated SIC. Another 4% of the area source SCCs are related to household activities that are indexed to population. The USEPA has developed the economic growth analysis system (EGAS, http://www.epa.gov/ttn/chief/emch/projection/index.html) to generate activity growth factors used in the development of emission inventory. We assign 30% area source SCC to a particular SIC following the EGAS mapping. The mapping of the remaining 50% of the area source SCC to SIC is based on our judgment through analysis of SCC and SIC coding. For example, SCC 2801700001 describes the emissions from applications of anhydrous ammonia to crop production. We assign it to SIC 01 that represents the agricultural crop production. Finally, we use the VMT data to estimate EMI for on-road mobile sources. The grouping is based on two mobile source categories—light-duty vehicles (LDV, e.g., passenger cars/vans and pick-up trucks) and heavy-duty trucks and buses. The SCC–SIC mapping is also key to the generation of future NEI-like emission inventory through the application of SIC-based growth factors to existing emission inventory, e.g., NEI99.

2.2.2. Time-varying EMI

Growth of population and the economy tends to increase emissions. On the other hand, increasing social consciousness of environmental protection and pressing demand of sustainable development has led to tightening of laws and regulations to cut emissions. Technological advances enable industries

and consumers to achieve greater emission reduction without compromising the volume of production. Continuous study and search of alternative and cleaner energy sources will also help to curb emissions. Further, the composition of the economy is changing; for example, in the Chicago region, manufacturing has declined from over 32% of total employment in 1970 to around 16% in 2005. A concomitant increase in service employment has thus changed the composition and quantity of pollutants over the same period. The significance of each phenomenon affecting emissions depends on the emission scenario considered. In order to permit the description of a wide range of scenarios it is necessary that the EMI be a function of time. Fundamentally, we have to go down to the SCC process level and apply any currently/potentially available or future likely technology to examine and develop time-varying EMI. However, due to lack of data and resources, and more importantly due to the extremely nonlinear and uncertain nature of human behavior and technological change, this approach is difficult to apply and to achieve a fast, yet reasonable, emission scenario development.

In this study, we take an alternative approach to develop time-changing EMI. We construct the NEI99-like inventories using the NEI air pollutant emissions trends data (http://www.epa.gov/ttn/chief/trends) to scale emissions in NEI99 to those in the years from 1970 to 2002. We then compile the emission activity data for the same period of time using results from CREIM and historical records from the US Department of Transportation, US Department of Energy, and US Census Bureau. Based on the SCC–SIC mapping method described in the previous section, we calculate sectoral EMI for the years from 1970 to 2002. Subsequently, we compute the average annual percentage change in EMI from each activity. This average annual EMI change reflects, collectively, the pace of historical technological, economic, and policy changes. By assuming that the average EMI change rate continues into future, we can project a time-varying EMI for each activity in response to a variety of factors.

2.3. Emission scenario development

For the present study, we treat two broad families of emission scenarios: constant EMI and changing EMI. In the constant EMI family, we assume that the current EMI will remain constant into the future. Therefore, all emission changes result from activity changes. Such activity changes include, but are not limited to, economic structural changes (e.g., outsourcing), transportation pattern changes, energy structural changes, population changes, and policy changes. CREIM is equipped with the capability to simulate those changes under different assumptions and conditions. The US federal agencies have developed different scenarios of future energy production and consumption. Combining these activity change scenarios with constant EMI leads to different emission scenarios. The projection of future emission changes with an assumed constant EMI emphasizes the impact of economic change on emissions.

The changing EMI family assumes that EMI will change in the future according to changes over the historical period. In combination with all activity change scenarios used in the constant EMI family, we are able to develop future emission scenarios considering both EMI and emission activity changes. Once future emissions are estimated for each activity, we can develop activity-based emission growth factors and calculate SCC-based emissions using the SIC–SCC look-up tables developed in Section 2.2.1. This provides us with a rapid, yet flexible, way to generate emission inventories in support of various AQM studies and decision makings.

3. Chicago case study

The developed emission inventory model is first applied to the Chicago metropolitan area that covers Cook, DuPage, Kane, Lake, McHenry, and Will counties. The pollutants considered are the criteria pollutants carbon monoxide (CO), nitrogen oxide (NO_x), sulfur dioxide (SO_2), and particular matter (PM10 and PM2.5 with diameter less than 10 and 2.5 μm, respectively). In addition, volatile organic compound (VOC) and ammonia (NH_3) are also included. Table 1 lists the emissions in the Chicago metropolitan area reported in the NEI99. The 1999 total economic outputs in Chicago area is approximately $456 billion ($1992).

3.1. Results of EMI

We calculated the EMI based on the present emissions (NEI99) and activity levels for the Chicago metropolitan area. Table 2 lists the top three sectoral EMI and top three emitters of each

Table 1
Pollutant emissions (ton year^{-1}) in the Chicago metropolitan area from NEI99

County	CO	NH$_3$	NO$_x$	PM10	PM2.5	SO$_2$	VOC
Cook	1,498,261	10,531	209,427	46,039	24,835	63,200	251,703
DuPage	277,415	1251	31,159	16,243	5720	3143	41,663
Kane	59,400	1599	9874	18,356	4784	1360	15,452
Lake	201,559	783	26,735	16,435	5669	21,355	36,103
McHenry	48,460	1225	6184	15,492	3649	640	9723
Will	103,897	2385	54,055	27,675	8175	93,450	21,195
Total	2,188,991	17,774	337,434	140,240	52,833	183,148	375,839

Table 2
Top three sectoral EMI and top three emitters (EMS) of each pollutant[a]

CO		NH$_3$		NO$_x$		PM10		PM2.5		SO$_2$		VOC	
EMI	EMS	EMI	EMS	EMI	EMS	EMI	EMS	EMI	EMS	EMI	EMS	EMI	EMS
CX07	CX07	CX01	CX49	CX44	CX49	CX01	CX42	CX01	CX42	CX49	CX49	CX07	CX07
CX79	CX79	CX49	CX01	CX49	CX15	CX42	CX15	CX10	CX15	CX29	CX29	CX46	CX29
CX33	CX33	CX29	CX29	CX07	CX40	CX41	CX01	CX42	CX33	CX44	CX32	CX29	CX34

[a]CX01 = livestock, livestock products, and agricultural products; CX07 = agriculture, forestry, and fisheries; CX10 = mining; CX15 = construction; CX29 = petroleum and coal products; CX32 = stone, clay, and glass products; CX33 = primary metals industries; CX34 = fabricated metal products; CX40 = railroad transportation and transportation; CX41 = local and interurban passenger transit; CX42 = trucking and warehousing; CX44 = water transportation; CX46 = pipelines, except natural gas; CX49 = electric, gas, and sanitary services; CX79 = amusement and recreation services.

pollutant. Within the 53 CREIM sectors, CX07 (agriculture, forestry, and fisheries) has the largest CO EMI (320 ton million \$$^{-1}$), almost 30 times more than the second ranked sector, CX79 (amusement and recreation services, 12 ton million \$$^{-1}$). CX07 also has the biggest VOC EMI (25 ton million \$$^{-1}$). CX01 (livestock, livestock and agricultural products) ranks first in NH$_3$ (8 ton million \$$^{-1}$), PM10 (29 ton million \$$^{-1}$), and PM2.5 (6 ton million \$$^{-1}$) EMI. CX44 (water transportation) tops the list of NO$_x$ EMI (29 ton million \$$^{-1}$), followed by CX49 (electric, gas, and sanitary services, 8 ton million \$$^{-1}$). CX49 is the largest emitter of SO$_2$ per unit economic output (12 ton million \$$^{-1}$). Sectors with large EMI are not necessarily the ones with large total emissions. Emission activity plays its role. For example, although CX44 has the largest NO$_x$ EMI, its total NO$_x$ emissions are barely $\frac{1}{6}$ of those from CX49. CX01, which has the largest PM10 and PM2.5 EMI, trails CX42 (trucking and warehousing) and CX15 (construction) in total PM emissions.

In order to obtain the time-varying EMI of the Chicago area, we have first categorized all emission activities into seven groups corresponding to the 13

tier 1 classes reported in the NEI air pollutant emissions trends data set. These seven groups are (1) resources, (2) construction, (3) industrial, (4) electricity, (5) services, (6) residential, and (7) transportation. Fig. 2 displays the historical EMI change from 1970 to 2002 for five pollutants. It is interesting to find that the resources group experiences an overall increasing trend in EMI from 1970 to late 1990s, and subsequently reverses the trend. Similar behavior is observed in the EMI trend of the construction group. In general, the industrial and services groups see declining trends in EMI from 1970 to 2002, reflecting combined effects of tightened regulation, technological advances, and economic structural changes. The transportation group experiences a steady decrease in EMI of CO, NO$_x$, PM10, and VOC for the same period of time. The EMI for SO$_2$, however, remains fairly constant until 1990 before undergoing a dramatic reduction. The residential group displays a unique trend in EMI where CO and PM10 peak in the mid-1980s and then decline steadily, while the EMI of NO$_x$ stays flat before climbing up to 50% higher than 1970 level in the 1990s. The electricity group displays a
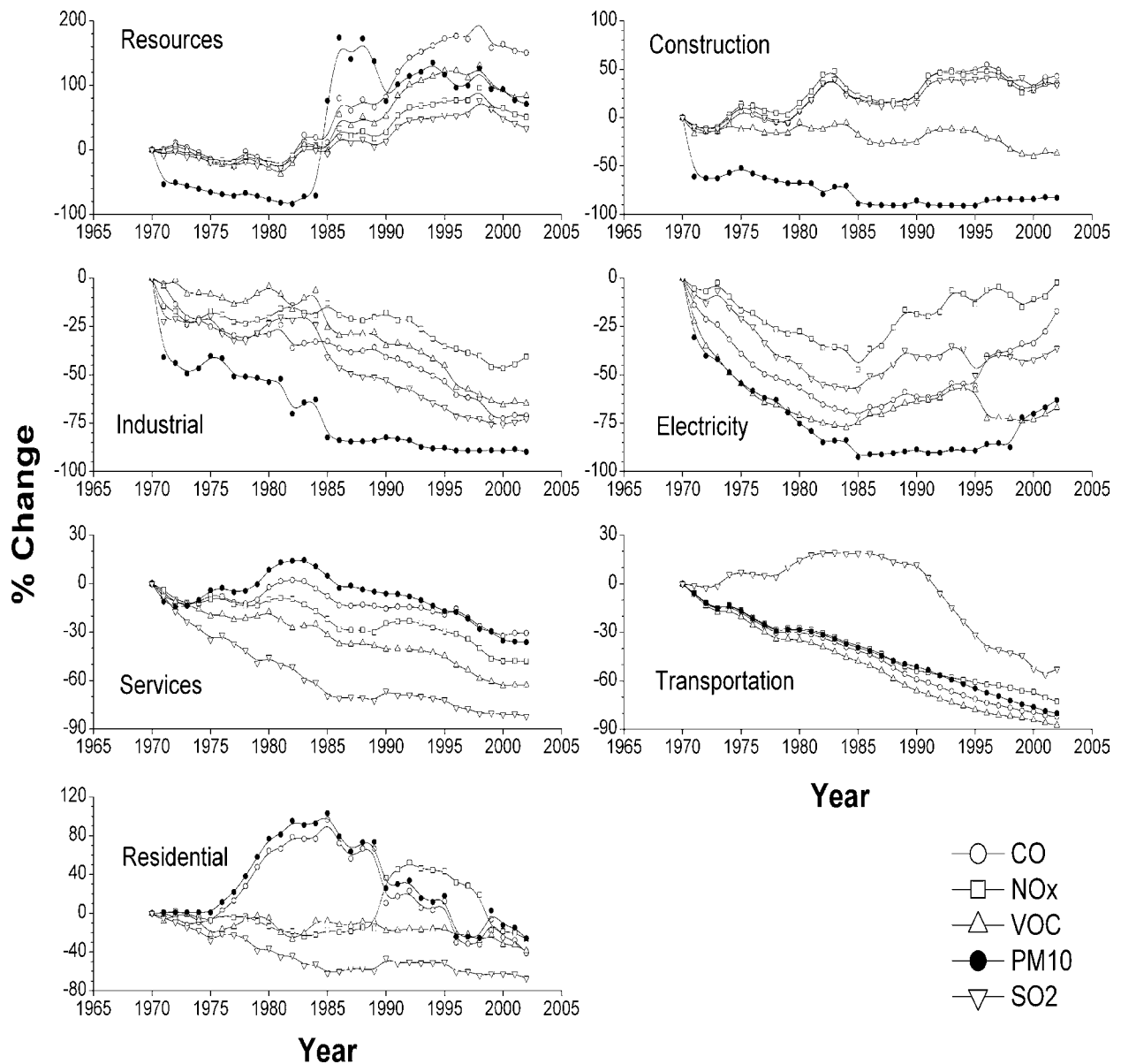
Fig. 2. EMI change from 1970 to 2002 for seven activity groups (relative to 1970) in the Chicago metropolitan area.

"U" shape of EMI evolution. The collections of trends data of NH_3 and PM2.5 emissions have not been started until 1990. From 1990 to 2002, emissions of these two pollutants decrease steadily in industrial, services, and residential, but increase in electricity. The resources group experiences an upward trend of both pollutants in the early-mid-1990s but downward since then. In construction, NH_3 and PM2.5 emissions stay at a relatively constant level in the early-mid-1990s but show different trends since then—PM2.5 goes up and NH_3 slides down. The transportation group sees a

steady decrease in PM2.5 but increase in NH_3 emissions. We are currently attempting to explain the underlying causes of the behavior of the various EMI, and will summarize the results in a separate paper.

We have calculated the average annual EMI change rate (%) for the seven activity groups (Table 3) and extended these rates into the future according to

$$EMI_t = EMI_0 \times \left(1 + \frac{\text{rate}}{100}\right)^n, \qquad (2)$$

Table 3
Average annual EMI change rate (%) for seven activity groups in the Chicago metropolitan area

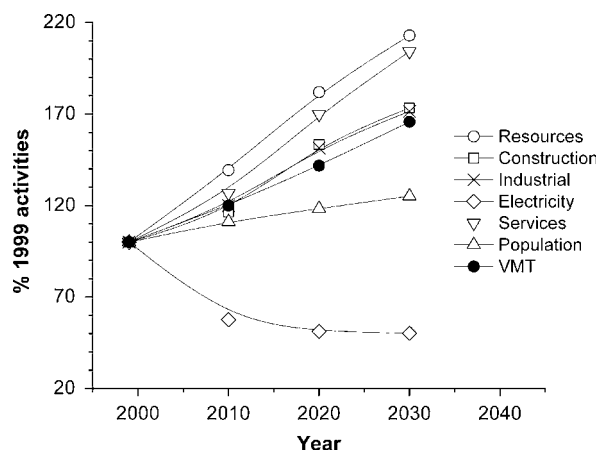|	Resources	Construction	Industrial	Electricity	Services	Residential	Transportation
CO	0	0	−3.56	−0.10	−1.07	−0.54	−5.20
NH₃	0	−5.64	−14.12	0	−11.94	−6.62	0
NOₓ	0	0	−1.49	0	−1.96	−0.24	−3.94
PM10	0	−1.68	−5.46	0	−1.31	−0.08	−4.88
PM2.5	0	0	−3.90	0	−2.88	−2.88	−8.22
SO₂	0	0	−3.68	−1.03	−4.92	−2.88	−2.16
VOC	0	−1.17	−3.00	−2.73	−2.97	−1.24	−6.22

Fig. 3. Changes of emission activity levels (relative to 1999) in the Chicago metropolitan area.

where EMI_t is EMI for future year t, EMI_0 is base year (1999) EMI, rate is the average annual EMI change (%), and n is the number of years from 1999. For this study, we assume that there is no EMI change into future (i.e., rate = 0) if the historical average annual EMI change is positive. The EMI change rates listed in Table 3 are then assigned to each CREIM sector.

3.2. Emission scenarios

Fig. 3 illustrates the projected future emission activity relative to the 1999 level in the Chicago metropolitan area up to 2030. As expected, the Chicago economy as a whole will continue growing. By 2030, outputs from resources and services will double in comparison to 1999. Construction and industrial are predicted to increase by approximately 70%. During the same time period, the Chicago population is projected to grow by approximately 25%, and people are expected to drive 65% more. Electricity is the lone group to see a reduced activity, declining by nearly 50% by 2030.

We developed two families of emission scenarios based on the emission activities projected in Fig. 3: constant EMI (scenario 1) and changing EMI (scenario 2). Under scenario 1, any future emission changes are driven only by future activity level. In line with emission activity changes, total emissions increase over the next 30 years (Table 4). However, the magnitude of emission change varies across pollutants. Under the constant EMI assumption, this magnitude difference reflects the economic structure change in the Chicago metropolitan area. If the economic structure were fixed from 1999 to 2030, the demand–supply relations among economic sectors would remain the same throughout 2030. It implies that by 2030, the output should change at the same rate across all the economic sectors, which results in the uniform change rate of emissions of every pollutant. It is unnecessarily true if the economic structure is changing. For example, electricity group is the single largest SO_2 emitter accounting for over 40% of total emissions in the Chicago metropolitan area. The severe activity reduction in electricity from 1999 to 2030 largely contributes to the small increase in SO_2 emissions by 2030.

Under scenario 2, in addition to changes in aforementioned emission activities, future EMI changes following Eq. (2) using the historic rates of EMI change listed in Table 3. As compared to the constant EMI scenario (Table 4), projected emissions under changing EMI scenario are significantly reduced, reflecting the effects of continuing trends of technological advances and ever-tightening environmental regulations. In the case of changing EMI, CO emissions are reduced by 56% in comparison with the constant EMI case in 2030. Emissions of NO_x, PM10, PM2.5, SO_2, VOC, and NH₃ are reduced by 52%, 35%, 48%, 60%, 59%, and 11%, respectively, by 2030.

Table 4
Projections of seven pollutant emissions (ton) in the Chicago metropolitan area

| Pollutant	1999	Constant EMI			Changing EMI		
		2010	2020	2030	2010	2020	2030
CO	2,188,991	2,635,157	3,260,430	3,848,122	1,802,386	1,742,577	1,702,227
NH$_3$	17,774	19,878	22,193	24,137	18,416	19,960	21,511
NO$_x$	337,434	401,638	479,772	551,425	304,648	288,415	265,071
PM10	140,240	180,117	230,372	261,784	151,772	169,268	169,414
PM2.5	52,833	63,112	78,148	87,884	48,003	48,635	46,006
SO$_2$	183,148	176,989	199,049	207,217	127,630	105,546	83,268
VOC	375,839	449,558	547,868	621,024	311,562	287,642	255,891
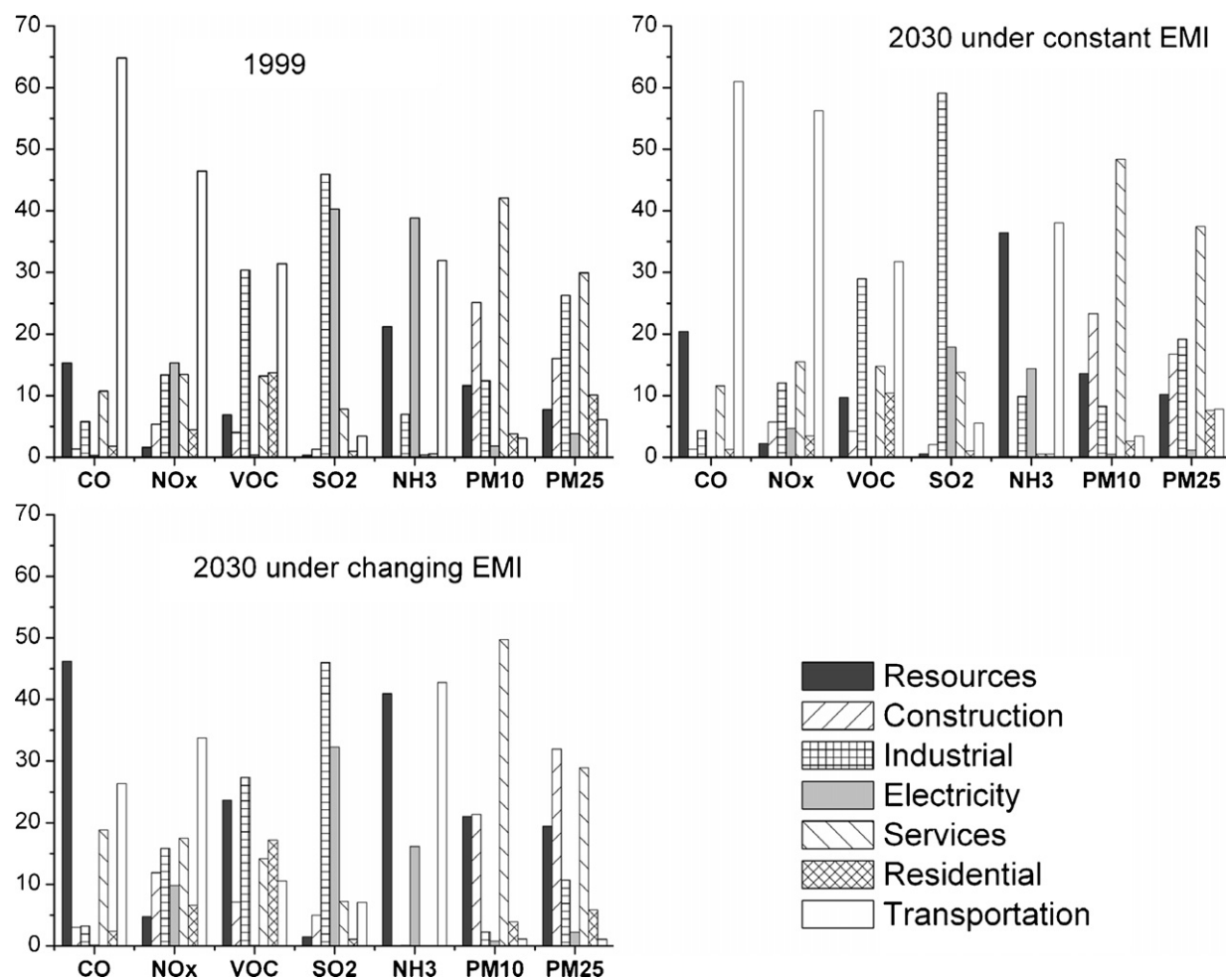
Fig. 4. Percentage distributions of pollutant emissions among seven activity groups in the Chicago metropolitan area.

Fig. 4 displays the evolution of percentage distributions of pollutant emissions among seven activity groups. The difference between 1999 and 2030 constant EMI cases reflects the economic structure changes over the time. In agreement with emission activity changes (Fig. 3), the portions of emissions from resources and services increase and those from electricity decrease. The dramatic drop

of activity in electricity makes industrial the lone dominant SO_2 emitter. Meanwhile transportation remains the important contributor to emissions of CO, NO_x, and VOC. Under the changing EMI scenario, emissions change upon the lump effects of economic structural change, as well as changes in technology and policy. Due to the different technology diffusion rates (Table 3) among emission activities, the relative contribution to emissions from each activity changes at a different pace. In comparison with the constant EMI case, overall percentages (the sum of percentage of every pollutant emissions within an activity) from resources and construction, which experience less EMI improvements, increase significantly. On the other hand, transportation and industrial that see the large EMI improvements have great reductions in emissions, thus their portions in total emissions decrease remarkably. It suggests that at some stage the used-to-be-less-important sources may play dominant roles in pollutant emissions. This dynamic feature requires prompt technology transfer and policy reactions to further curtail emissions. Note that Fig. 4 is a summary of more detailed emission distributions among 53 CREIM sectors and residential and on-road transport activities (not shown). Based on those detailed sectoral emission projections, we developed emission growth factors to generate future emissions readily available for air quality study.

3.3. Comparison to EGAS and IPCC scenarios

The USEPA designs the EGAS to forecast economic activity in support of future emission inventory development. We used the EGAS version 5.0 to calculate the economic sectoral growth factor for the 6-county Chicago area. Multiplication of the growth factors with the 1999 emissions yields future emissions comparable to our model predictions under the constant EMI scenario. Fig. 5 shows the results of the comparison. In general, the EGAS predicts higher emissions of every pollutant although the magnitude of discrepancy varies among pollutants. This reflects the fundamental difference in formulating the future of the Chicago economy by the EGAS and our model. For example, the EGAS forecasts a 70% increase in sector CX49 (electric, gas, and sanitary services), while the CREIM model predicts a 50% decrease, which explains the large discrepancy in SO_2 projections between two studies. Other significant differ-
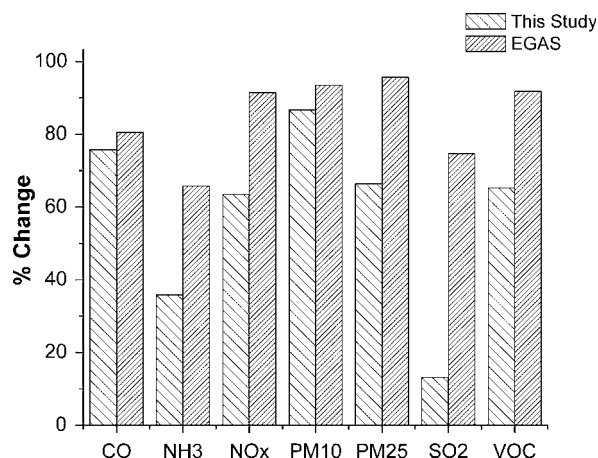

Fig. 5. Percentage change of emissions between 1999 and 2030 projected by this study assuming constant EMI and by EGAS.

ences are that the CREIM model projects sizeable reductions in outputs from sectors CX10 (mining, 9%), CX33 (primary metal production, 71%), and CX34 (fabricated metal production, 35%), while the EGAS forecasts increases of 48%, 147%, and 124%, respectively. The comparison shows the important role of emission activity level in future emission projections. The ability and flexibility of the CREIM model to provide a wide range of future economic activities is essential to developing a suite of emission scenarios for various impact studies and decision makings.

The SRES from IPCC (IPCC, 2000) outlines a series of emission scenarios. We compared our two scenarios, constant EMI and changing EMI, to the marker scenarios of the A1Fi, A2, B1, and B2 families in the SRES. The A1Fi scenario is fossil intensive in the A1 family that depicts a world of rapid economic growth and quick spread of new technologies. It generally features high emissions in the future. The A2 family describes a very heterogeneous world and emphasizes the regional-oriented developments. The B1 family features a convergent world and rapid economic structure change toward a service and information economy, which results in lower emissions in the future. The B2 family emphasizes local solutions to economic, social, and environmental sustainability with a lower population growth and slower technology transfer rate (IPCC, 2000). We chose the scenarios listed under the OECD90 for comparison (Fig. 6). In general, emissions under the constant EMI scenario are higher than any IPCC scenarios, and emissions under the time-varying scenario are among the
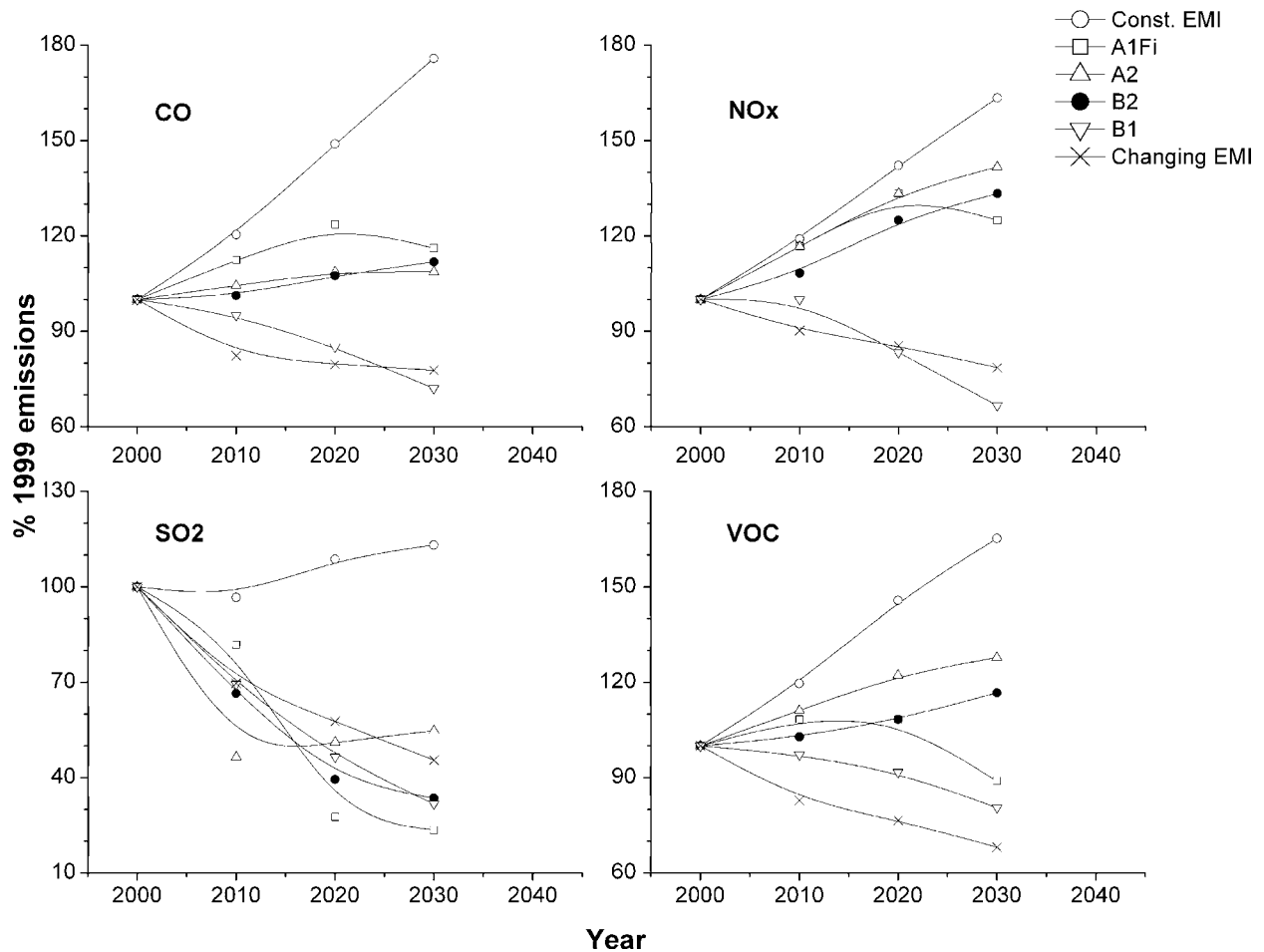
Fig. 6. Comparison of emissions from this study to IPCC SRES scenarios.

lowest. This indicates that our model predictions reasonably represent a wide range of scenarios. In a similar fashion to the IPCC projections, we cannot provide the probability of which case is more likely, or to provide an accurate emission prediction. Rather, we are building a framework that links emissions to projections of economic and other activities to produce scenario-based emission inventories that will be made available for impact studies.

4. Conclusion and discussion

In support of ongoing future climate and air quality studies, we have developed an econometric-emission model to project future emissions specific to regional changes in both emissions generation and the structure of the economy. Through I–O table and economic sectoral EMI, the model links

the complex demand–supply relationship to pollutant emissions. One important aspect of this study has been the development of the sectoral EMI, which requires the mapping of SCC code used in the NEI99 to SIC code applied in the CREIM. We do the mapping through detailed inventory scrutiny, literature search, and expert judgment. We use the population and VMT data to develop the EMI for emissions from on-road mobile sources and household, which are difficult to be mapped to any economic sector. One advantage of SCC–SIC mapping is that we can develop SIC-based emission growth factors using econometric-emission model, and then apply these growth factors to any existing emission inventory (e.g., NEI99) to generate future emissions in a format that can be readily available to emission processing models, e.g., SMOKE (Houyoux et al., 2000), to support air quality and other impact studies. Based on historical emissions

Table 5
Changes of emissions between 1999 and 2030 in the Chicago metropolitan area (%)[a]

	CO	NH$_3$	NO$_x$	PM10	PM2.5	SO$_2$	VOC
Constant EMI	+76	+36	+63	+87	+66	+13	+65
Changing EMI	−22	+21	−21	+21	−13	−55	−32

[a]"+" indicates increase; "−" indicates decrease.

and economic data, we also develop a mechanism to account for the EMI change over time, a measure that collectively takes into account changes in technology and policy.

We apply the model to project pollutant emissions in the Chicago metropolitan area up to year 2030. Table 5 summarizes the percentage changes of 2030 emissions (relative to 1999) under the constant EMI and changing EMI scenarios. The large difference in emission projections under the two scenarios reflects the key role of technology changes in emission projections. Under either scenario, the magnitude of emission changes varies among different economic sectors, which makes the development of SCC-based emission growth factor possible. Comparison of the results from this study to those from the EGAS and IPCC scenarios indicates the importance of the driving force assumptions in emission projections. It also indicates the capability of our model to produce a wide range of emission scenarios specific to selected regions.

We acknowledge that our method to estimate time-varying EMI and its coupling with the CREIM is rather simplistic, in the sense that we do not incorporate, explicitly, the economic consequences from the EMI change into the CREIM. That may lead to mismatch of EMI to the CREIM results, and will be one improvement in future work. Meanwhile, we intend to re-specify the current discrete-time CREIM in continuous time. There are three benefits with the continuous-time approach: (1) continuous-time models provide a better characterization of ongoing aggregate economic activity than discrete-time models, and permit better handling of mixed samples (i.e., samples including data on stocks, flows, derivatives, point observations, and period averages); (2) the estimates of continuous-time system parameters tend to be more efficient than their discrete-time system counterparts (Phillips, 1993), and estimates of adjustment parameters, hence adjustment lags, are independent of

the observation interval; (3) once the parameters of a continuous-time system have been estimated, the model can be solved for any time interval. The latter advantage may be more important to this study since it can provide us with economic projections beyond a 30-year horizon, the limit the discrete-time models can reach. Finally, work has commenced on design and implementation of the decision support system (DSS) through which we intend to make the results of the study dynamically available on the web.

However, the most important findings from the analysis are the important roles played by technological change in two senses—changing the structure of the economy and changing the quantity of pollutants emitted per unit of production. Further analysis on the sensitivity of assumptions surrounding changes in these characteristics will be important, as a way of strengthening the findings and thus focusing attention on sectors or combinations of sectors that are likely to be major contributors to deterioration of air quality over the next several decades.

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